Scanning the Issue

Special Issue on Flexible Electronics Technology, Part 1: Systems and Applications

Flexible electronics encompasses a rather diverse range of device and materials technologies that are built on flexible and conformal substrates. Critical technology components include organic and inorganic semiconductor materials, micro- and nanostructured materials, printed interconnects and circuits, thin-film transistors (TFTs), thin-film photovoltaics, and mobile energy sources, and new methods for processing on large flexible substrates. Flexible electronics is becoming an exciting research area drawing active participation of scientists and engineers from both academia and industry. While the technology shows great promise, it is still nascent, and advances in many areas are needed before large-scale applications start to flourish.

The two issues of the PROCEEDINGS OF THE IEEE on flexible electronics provide a comprehensive review of research worldwide in flexible micro- and macroelectronics. The articles provide broad coverage across two major themes: *large area electronics and systems* (focused on devices, related fabrication techniques, and applications) that appear in the current issue, and *materials and manufacturing technology* (including new materials, substrates, and manufacturing tools), which will appear in the August issue.

Despite its relative infancy, the field is rapidly proliferating spawning exciting and vibrant research areas, driven by new applications. For example, amorphous and low-temperature polysilicon and organic semiconductor materials is one research area that has benefited tremendously from applications in displays. The primary research emphasis at major laboratories is no longer confined to materials and device technologies, but is beginning to expand into process and device integration that enable commercial applications.

Thin-film devices and circuits based on silicon and various organic semiconducting materials and printable electronics on flexible substrates form a large part of the discussion in this issue, although we do also have a number of papers detailing how flexible electronics can be integrated into systems.

Flexible electronics could become a key enabler for a number of platform technologies such as printed transistors, embedded power sources, and integrated sensing devices. By replacing the rigid substrate with one that is mechanically flexible will enable a number of unique applications for displays and imagers. Other major applications include distributed sensors, electronic textiles, electronic paper, and large circuits that can be conformably fitted on curved objects and surfaces as needed in biomedical imaging and structural monitoring.

Because the technology for making flexible electronics is not fully mature, there are several areas that require major advances. These include substrate development with adequate thermophysical properties, low temperature processing of electronic-grade materials on flexible substrates, including techniques for substrate handling, reliability of packaging and encapsulation technologies, and very importantly, developing the means to power these circuits. If these difficulties can be overcome at reasonable cost, a large number of applications can be enabled using flexible electronics technology.

For example, development of efficient and flexible energy storage and portable power sources is essential for flexible electronics to become a viable technology. Indeed, progress in thin-film photovoltaics is very encouraging, and integration of flexible batteries with photovoltaics could provide an innovative means to power these circuits. Recent developments in organic semiconductor materials and micro-/nanocrystalline Si, could lead to higher speed analog and digital electronic circuits, promising total system integration on the same flexible substrate. Advances in new semiconductor materials and associated methods for fabricating devices and circuits over a large area, coupled with advances in new flexible substrate materials with respect to chemical ruggedness, glass transition temperature, and dimensional stability, will spawn new and unique application areas. A good example is the solid-state lighting panel on flexible substrates, realized using potentially low cost roll-to-roll manufacturing techniques.

While flexible electronics presents a number of useful attributes, the difficulty has been to identify unique applications that expedite the technology to maturity. Historically, the maturity process happens through adoption of the new technology in a unique application that is otherwise not possible. In the first paper, "Macroelectronics: Perspectives

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on Technology and Applications," Reuss *et al.* describe a number of applications of flexible electronics in monitoring mechanical integrity of large structures such as airframes, distributed electronics for large space-based antennas, and potential applications in robotics and sensory circuits. The authors highlight the need for further advances in materials and manufacturing technology, engineered flexible substrates with enhanced mechanical and chemical properties, along with device concepts and architectures that are uniquely suited for realization of ultralarge circuits.

Mechanical stress induced performance degradation is a major problem for transistors build on flexible substrates. In "Functional Pixel Circuits for Elastic AMOLED Displays," Servati and Nathan describe pixel architectures that can compensate for threshold shifts in thin-film transistors (TFT) due to changes in the operational environment, and review the effects of mechanical strain on device performance. While this paper is focused on silicon-based flexible electronics, the following paper, "Flexible Organic LED and Organic Thin-Film Transistor," by Zyung *et al.*, deals with flexible optoelectronics using organic LEDs (OLEDs) and organic transistors. Specifically, the focus of this paper is on high-efficiency OLEDs driven by organic TFT circuits.

Seamless integration of transistors, light-emitting and detection elements, and other active circuitry is essential to integrate functional systems out of flexible electronics. While a number of active and passive components on flexible substrates have been demonstrated, the integration of various circuit elements is just beginning to occur. The following three papers highlight recent progress towards this goal. Bhattacharya *et al.*, in "Organic LED Pixel Array on a Dome," discuss the integration of OLED pixels on substrates which have been conformably shaped into hemispherical surfaces. Integration of TFTs and light-emitting pixels on conformably shaped surfaces has a number of unique applications. In "Flexible a-Si : H Position-Sensitive Detectors," Fortunato *et al.* describe the challenges of fabricating heterojunction position sensitive detectors. While the status of flexible TFTs, OLEDs, and image sensors and detectors is reasonably advanced, integration of memory elements will be a major challenge. This is mainly because of the higher degree of complexity of existing memory technology. Memories based on organic semiconducting material might provide a reasonable solution, but this is still in its exploratory stages. Ouyang *et al.*, in "Organic Memory Device Fabricated Through Solution Processing," describe organic nonvolatile memories based on electrical bistability observed in polymer films containing metal nanoparticles and small conjugated organic compounds.

One of the fabrication challenges for flexible electronics using Si TFTs is to get high performance without employing high process temperatures. While Si TFTs annealed at high temperatures show exceptionally good performance, translating this into devices processed at lower temperatures is a major challenge. One of the solutions being proposed is to enable low temperature annealing using excimer lasers. While excimer laser annealing at temperatures greater than 350 °C is becoming an established technology in the display industry, process temperatures have to be brought down to 150 °C or lower to be useful for processing polymer substrates. In "Poly-Si TFT Fabricated at 150 °C Using ICP-CVD and Excimer Laser Annealing," Han *et al.* demonstrate poly-Si TFTs with good performance with respect to transfer and current–voltage characteristics.

TFTs using amorphous and polysilicon have been studied for over three decades, and the fundamental device physics is relatively well understood. However, this is not the case with TFTs using organic semiconducting materials. Organic semiconductor materials represent a complex set of new materials, and the process of developing good models for device characteristics is only in its infancy. In "Extracting Contact Effects in Organic FETs," Hamadani and Natelson present a detailed study on the effect of contact resistance on the transport properties of organic FETs. Deen and Kazemeini, in "Photosensitive Polymer Thin-Film FETs Based on Poly(3-octylthiophene)," report on the transport characteristics and electrical performance of photosensitive polymeric TFTs under broadband white-light illumination. Polymer phototransistors are useful as high-efficiency photodetectors, since the organic semiconducting material can be suitably engineered to provide the desired photoresponse. However, for stable and reliable device operation, polymeric semiconducting materials that are intrinsically UV stable and less reactive with moisture are needed.

Printed electronics is a rapidly growing area of research with enormous potential for the fabrication of low-cost printed electronics. This issue contains four papers that describe in detail progress in this technology. In "Large Area Electronics Using Printing Methods," Parashkov *et al.* review different printing methods used in fabricating organic electronics. One of the promising applications for printed organic electronics is in RFIDs. In "Progress Towards Development of All-Printed RFID Tags: Materials, Processes, and Devices," Subramanian *et al.* outline the commercial requirements for RF tags and describe progress towards realizing an all-printed RFID. In "Printed Electrochemical Devices Using Conducting Polymers as Active Materials on Flexible Substrates," Chen discusses the development of various circuit elements such as diodes, rectifiers, and three-terminal and four-terminal transistors using printed organic materials. Identifying a complete material set necessary to realize printed organic electronics is very important. Chason *et al.*, in their paper "Printed Organic Semiconducting Devices," describe materials requirements and product opportunities for printed organic electronic devices. They also review device performance of organic transistors that were fabricated using printing processes and discuss the ongoing process of standards development for organic TFTs.

As deposition and crystallization of semiconductors on flexible polymeric substrates is a major problem, many approaches for the direct deposition of high-mobility semiconductors are being explored. One approach is to use highly crystalline nanowires that can be deposited and patterned, by transfer printing or solution casting, onto plastic substrates. McAlpine *et al.*, in "High-Performance Nanowire Electronics and Photonics and Nanoscale Patterning on Flexible

Plastic Substrates," describe how to form high-mobility nanocrystalline semiconductor materials to create flexible TFTs with excellent electrical properties.

In "Low-Temperature Deposition of Hydrogenated Amorphous Silicon in an Electron Cyclotron Resonance Reactor for Flexible Displays," Flewitt and Milne describe their research on low-temperature deposition processes for amorphous silicon, compatible with the use of transparent, plastic substrates. Finally, Tarighat *et al.*, in "Realization of Flexible Plasma Display Panels on PET Substrates," describe the development of a flexible plasma panel using polyethylene terephthalate (PET) substrates. While this is an interesting technical demonstration, PET is highly permeable to moisture, thus reducing the usable life of these plasma devices, unless highly effective encapsulation is deployed.

While this two-part special issue on flexible electronics is our attempt to provide a snapshot of current research in the field, it is by no means complete. The papers in both issues cover a large ensemble of topics ranging from flexible substrates, and substrate engineering, to advances in new materials, devices, circuits, and systems and associated integration challenges. Although the issue contains only a selected subset of topics, it does address the current status of this technology and guides the scientist and engineer to the primary sources of literature for further reading.

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He is a Member of the American Physical Society, the Electrochemical Society, the Materials Research Society, the Society for Information Displays, the International Society for Optical Engineering, and the Institute of Electrical Engineers (U.K.). He served as chair of the EDS-SSC society in the IEEE K-W Local Chapter, IEEE Newsletter Editor for Region 7, and received the IEEE/EDS Distinguished Lecturer Award in 2004. He is a member of the IEEE EDS Publications Committee and the IEEE EDS Sub-Committee on Organic and Polymer Devices. He chairs the 2005 IEEE Lasers and Electro-Optics Society Technical Committee on Displays, and the Displays Subcommittee in 2004 and 2005. He is an Editorial Board Member of IEEE TRANSACTIONS ON DEVICE AND MATERIALS RELIABILITY and the newly created IEEE/OSA JOURNAL OF DISPLAY TECHNOLOGY. He serves as Cochair of the Fall 2005 Materials Research Society Symposium M: Flexible and Printed Electronics, Photonics, and Biomaterials.

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